Asteroseismology

Introduction

No parts of the Universe are more difficult to observe directly than the interiors of the stars. With asteroseismology, we make use of the oscillations of pulsating stars to study their internal structures. The basic principles of asteroseismology are very much alike those developed by earth seismologists. The reason why stellar interiors can be probed from oscillations is that different oscillation modes penetrate to different depths inside the star. The observed frequency spectra are carefully characterized rendering information on the stellar interior. Different pulsation modes are discerned: acoustic (p)-modes with high frequency for which pressure is the dominant restoring force and gravity (g)-modes with lower frequency for which buoyancy is the dominant restoring force.

Why study the interiors of stars?

The substantial uncertainties in our understanding of stellar physics have a direct impact on the calibration of distances on extra-galactic scales, fixing the ages of the oldest stellar populations (which place tight constraints on cosmologies), and tracing the chemical evolution of galaxies. By providing detailed information about stellar interiors asteroseismology will reduce significantly these uncertainties, and therefore strengthen the foundations of these diverse and crucial areas of astrophysics. For example, while the ESA Cornerstone Mission Gaia will give positions and proper motions of stars to unprecedented accuracy, our ability to estimate accurate fundamental stellar properties — such as masses and ages — will remain a limiting factor in our ability to discriminate between different scenarios of formation and evolution of the Galaxy components (halo, thin and thick disk and bulge). Asteroseismology is able to provide such estimates to levels of precision and accuracy, and on stellar samples that are large enough, to overcome these limitations. There are also strong synergies with exoplanet studies. Asteroseismology will allow us to follow stellar cycles and to trace how levels of activity change as stars and their exoplanets age, giving insights on planetary habitability and key information for understanding the variability shown by our own sun.

Space-based data

The NASA *Kepler* Mission and the French-led CoRoT satellite have realised huge breakthroughs for the study of stars, in particular those that show solar-like oscillations. Asteroseismic datasets of unprecedented length are now available on thousands of stars, including hundreds of cool main-sequence and sub-giant stars, and on thousands of red giants. In addition, the missions delivered data for tens of pulsating stars in eclipsing binaries, opening up the field of binary and tidal asteroseismology. Within the SPACEINN programme we will develop and verify robust methodologies to exploit, in a timely manner, the full scientific potential of this ensemble not only for testing stellar evolution theory, but also for providing accurate masses and ages for galactic studies.

Ground-based data

We aim at fully realizing the benefits of exploiting simultaneous ground- based data, such as Doppler velocity observations and/or spectral line-profile data obtained with large telescopes and multi-colour photometry resulting from multi-site campaigns organized with smaller telescopes.

Solar-like oscillators

Solar-type and red-giant stars show rich spectra of solar-like oscillations, pulsations which are excited and intrinsically damped by turbulence in the outermost layers of the convective envelopes. In main-sequence stars the oscillations are predominantly acoustic in nature. However, in the sub-giant and in particular the red-giant phase, g-modes, for which buoyancy is the restoring force, become visible providing further exquisite information on the interiors of these stars. Results on the period spacings of these modes have for example provided the means to discriminate stars in different advanced stages of evolution (stars that would otherwise be hard to discriminate because they share very similar surface properties). The long datasets provided by Kepler are making it possible to resolve frequency splittings due to rotation, and inversions to recover the radial profile of the rotation are already being performed on sub-giants. I is also possible to use estimated frequencies to detect, and then constrain the properties of, small convective cores in main-sequence stars (which helps to better calibrate stellar ages) and to measure the depths of the convective envelopes (relevant to stellar dynamo theory). Solar-like oscillations have been detected in more than 100 candidate or confirmed exoplanet-hosting stars, providing crucial data to characterise the host stars and hence the orbiting planets. Whilst detected oscillations in several hundred solar-type and over 10,000 red-giant stars have also opened new possibilities for stellar population studies, with these data providing precise and accurate stellar properties for such work.

Heat-driven oscillators

While the asteroseismic potential of stars considerably more massive than the Sun, whose oscillations are excited by a heat mechanism or by tidal forcing, is less than for stars with oscillations triggered by stochastic forcing in outer convection zones, the uncertainties on their evolution are far larger. Hence the relative gain from seismic modeling, even if more limited than for solar-like oscillators, is equally valuable for those objects, particularly if the excited modes can be identified. Mode identification is the largest difficulty for seismic applications to massive stars, particularly when dense frequency spectra of high-order gravity-mode oscillations are detected. On the other hand, the simultaneous detection of self-driven pressure and gravity modes offers the potential to constrain both the inner core regions and the outer layers of the stars, and their successful modeling will have large impact on the stellar evolution theory. Given that the massive stars are mainly responsible for the production of all elements heavier than carbon, and that details of the internal mixing processes determine the amounts of such heavy-element production, massive star asteroseismology is expected to contribute significantly to the understanding of the chemical enrichment of the Galaxy.

Fundamental stellar parameters

Standard stellar models are based on many simplifying hypotheses and often ignore the effects of physical processes such as diffusion, convective overshooting, transport of angular momentum, and rotationally induced mixing in radiative regions. Inaccuracies in the descriptions of these quantities may lead to systematic errors in estimates of the fundamental stellar parameters. Data on stellar oscillations can provide the long-sought additional constraints needed to test the detailed physics of stellar interiors. For example, there are seismic signatures left by the locations of convective boundaries. It is therefore possible to pinpoint the lower boundaries of convective envelopes. These regions are believed to play a key role in stellar dynamos, and so this information is of great importance to stellar dynamo modelers. Furthermore, it is also possible to estimate the sizes of convective cores. Measurement of the sizes of these cores, and the overshoot of the convective motions into the layers above, is important because it can provide an accurate calibration of the ages of these stars. The mixing implied by the convective cores, and the possibility of mixing of fresh hydrogen or helium fuel into the nuclear burning cores – courtesy of the regions of overshoot – affects the stellar lifetimes drastically.